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1. Your reference — P10080

2. Patent application number *(The Patent Office will fill in this part)* — 0220228.1

3. Full name, address and postcode of the or of each applicant *(underline all surnames)* — HERIOT-WATT UNIVERSITY RICCARTON EDINBURGH

   Patents ADP number *(if you know it)* — ~~0581418001~~

   If the applicant is a corporate body, give the country/state of its incorporation — N/A 5814418001 I.J

4. Title of the invention

   ABSOLUTE PHASE MEASURING SENSOR

5. Name of your agent *(if you have one)* — ~~TECHNOLOGY & RESEARCH SERVICES HERIOT-WATT UNIVERSITY RICCARTON EDINBURGH EH14 4AS~~

   "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* — CRUICKSHANK + FAIRWEATHER 19 HOPE STREET EDINBURGH EH2 4DB.

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
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Optimum Wavelength Selection for Multi-Wavelength Absolute Phase Measuring Sensors

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1.0 Background

There exists a multitude of interferometric based sensors for measuring the phase of electromagnetic waves. Measurands that effect the phase of a wave include: deformation [1], vibration [2], refractive index variation due to density changes and a host of techniques for single point and whole field profilometry from synthetic aperture radar (SAR) [3] to fringe projection [4]. In an interference pattern there are two elements that contribute to the phase measurement dynamic range: the sub-fringe phase resolution and the number of fringes (fringe orders) spanned by the measurement. There is typically a simple function relating the measured optical fringe phase to the desired measurand. The process of phase measuring produces sub-fringe resolution, typically $1/100^{th}$ to $1/1000^{th}$ of a fringe. The sub-fringe resolution is calculated via either phase stepping [5] or Fourier transform techniques [6]. However, the interferometric phase is calculated using an inverse trigonometry function with principal values over the range $-\pi$ to $+\pi$ at best. Therefore the required phase information is 'wrapped' into an interval with sharp discontinuities in the data at the edges of that interval which must be spatially or temporally unwrapped to obtain the fringe order information.

2.0 Current State-of-the-Art

A generic problem common to most interferometric techniques is the determination of absolute fringe order in interferograms containing phase discontinuities or spatially or temporally discrete samples. Conventional interferometric analysis for single point data relies on a temporal scan to measure the relative phase change in going from one state to another. In the case of whole field data, a spatial unwrapping is achieved using an appropriate algorithm giving relative information on the state (or change of state) across the image field [7].

One well established research area for absolute phase measurement is fringe projection for profilometry where the synthetic wavelengths produced can be varied relatively easily. Therefore, techniques based on temporal phase unwrapping may be applied. Huntley et al introduced a temporal phase unwrapping approach using a reverse exponential series of projected fringes given by: $s, s-1, s-2, s-4, \ldots, s/2$ [8]. Here, the unwrapping is performed between consecutive phase measurements to scale the fringe order calculated at the subsequent wavelength. Absolute fringe order is obtained as the unwrapping is performed at each pixel independently along the time axis. The number of projected fringe frequencies required has been reduced to $(\log_2(s)+1)$. For each projected fringe frequency four phase stepped images are obtained to determine the wrapped phase values in the interval $-\pi$ to $+\pi$. For example, to measure over a range of 32 fringes 6 sets of 4 frames are needed, and for 128 fringes 8 sets of 4 frames. Therefore, considerable time is required to obtain the image frames, and as each image may contain >1MB of information a significant data processing problem is generated.

3.0 Basis of the Invention

We have devised a novel strategy for absolute fringe order identification in multi-wavelength heterodyne interferometry based on optimum selection of the wavelengths to be used. A theoretical model of the process has been developed which allows the process reliability to be quantified. The methodology produces a *wavelength selection* which is optimum with respect to the minimum number of wavelengths required to achieve a target dynamic range. Conversely, the maximum dynamic range is produced from a given number of *optimally selected* wavelengths utilised in a sensor. The new concept introduced for optimum wavelength selection is scalable, i.e. from a two wavelength system to a three wavelength system, from three wavelengths to four etc. Therefore, whilst the previous technology allowed 2^{N-1} fringes to be counted absolutely where N is the number of fringe frequencies used, the new technique scales as n^{N-1}, where n is an arbitrary real number limited by phase noise of a practical interferometer.

3.1 Theoretical Development

3.1.1 Two Wavelength Interferometry

In two wavelength heterodyne interferometry to eliminate step height ambiguity the difference in the number of fringes projected across the field of view must be ≤1. Let the number of projected fringes across the field be $N_{\lambda i}$ for the i^{th} wavelength; then $N_{\lambda 1} - N_{\lambda 2} < 1$ with $N_{\lambda 1} > N_{\lambda 2}$. The difference in wrapped phases calculated at the two wavelengths, a heterodyne function, can be expressed as a phase within the interval $-\pi$ to π and will consist of a monotonic ramp across the image. A convenient representation is to calculate a

discrete phase level for each of the fringe orders corresponding to $N_{\lambda 1}$. This is obtained by subtracting a scaled version of the wrapped phase at $N_{\lambda 1}$ from the heterodyne function - the scaling factor being given by $(N_{\lambda 1} - N_{\lambda 2})/N_{\lambda 1}$. In practice, such a discrete level heterodyne function can only identify a limited number of fringe orders owing to the presence of phase noise. Each $N_{\lambda i}$ is known, as it is set in a white light system or can be measured in coherent systems [9].

Each wrapped phase measurement contains phase noise, which is modelled as a Gaussian distribution with zero mean and a standard deviation of σ_ϕ [10]. The heterodyne function then contains noise with a standard deviation given by $\sqrt{2}\sigma_\phi$. We define a process robustness of 6σ, corresponding to a probability of 99.73% success in fringe order identification within the measurement system. Therefore, the discrete phase levels must be separated in phase by at least $6\sqrt{2}\sigma_\phi$. Hence, for 6σ reliability the number of fringes which can be correctly identified is limited by:

$$N_{\lambda 1} \le \frac{2\pi}{6\sqrt{2}\sigma_\phi}.$$

Defining the measurement dynamic range as the product of the phase resolution and the number of fringes successfully numbered. Therefore, for a phase resolution of 1/100*th* of a fringe, 12 fringes can be numbered to 6σ reliability, giving a dynamic range of 1200, which is insufficient for most engineering applications.

3.1.2 Optimally Selected Wavelengths in N Wavelength Interferometry

The introduction of a third projected wavelength allows the generation of two independent heterodyne functions containing N_{DL1} and N_{DL2} discrete levels, where $N_{DL1} \times N_{DL2} = N_{\lambda 1}$. The discrete phase levels in each modified heterodyne function will be separated by:

$$\vartheta_{DL1} = 2\pi/N_{DL2} \text{ , and } \vartheta_{DL2} = 2\pi/N_{DL1} \quad (1)$$

In this arrangement it is found that as ϑ_{DL1} increases ϑ_{DL2} decreases. Therefore, for maximum overall reliability in fringe order identification the optimum set of projected fringe wavelengths is given by the symmetrical arrangement where $\vartheta_{DL1} = \vartheta_{DL2}$ and $N_{DL1} = N_{DL2} = \sqrt{N_{\lambda 1}}$. If the number of discrete levels is not balanced the effect is to increase one of N_{DL1} and N_{DL2}, thereby bringing ϑ_{DL1} or ϑ_{DL2} closer to the noise limit. Hence, from equation (1), the optimised 3 wavelength approach the condition for 6σ reliability fringe order identification is given by,

$$\sqrt{N_{\lambda 1}} \le \frac{2\pi}{6\sqrt{2}\sigma_\phi}. \quad (2)$$

The number of fringes which may be heterodyned reliably in an *optimum* 3 wavelength heterodyne setup is therefore the *square* of that for the two wavelength case for the same phase measurement noise.

Equations 1,2 are used to define general expressions relating the numbers of projected fringes at the N wavelengths. By assuming $N_{f_0} > N_{f_i}$ and $N_{DL1} \times N_{DL2} \times \ldots \times N_{DLN} = N_{f_0}$, with $N_{DL1} = N_{DL2} = \ldots = N_{DN}$, for optimum noise immunity, one general approach is given by,

$$N_{f_i} = N_{f_0} - \left(N_{f_0}\right)^{\frac{i-1}{\lambda-1}}, \text{ for } i = 1,2,\ldots,\lambda \quad (3)$$

where: λ number of wavelengths, N_{f_0} number of fringes in the largest fringe set, N_{f_i} number of fringes in the i^{th} fringe set. The term $N_{f_1} = 0$ is included in order to generalize the expressions that follow. The general formulas to calculate the fringe order are given by:

$$DL_i = H_{0,i} - \frac{N_{f_0} - N_{f_i}}{N_{f_0} - N_{f_{i+1}}} \times H_{0,i+1} \quad (4)$$

$$IDL_{i+1} = NINT\left[\left(DL_i + 2\pi \times IDL_i\right) \times \left(\frac{N_{f_0} - N_{f_{i+1}}}{N_{f_0} - N_{f_i}}\right) \times 2\pi\right] \quad (5)$$

for $i = 1,\ldots,\lambda - 1$, where DL_i is the i^{th} discrete level function, IDL_i is the i^{th} integer discrete level and $H_{0,i}$ is the heterodyne between the 0 and i^{th} wrapped phase map. The recursive relationship for the integer discrete level functions is initialised by setting $IDL_0 = 0$. The fringe order for the wrapped phase map with N_{f_0} fringes is given by IDL_λ from equation (5).

For example using four synthetic wavelengths with $N_{f_0} = 64$, then $N_{f1} = 63$, $N_{f2} = 60$, $N_{f3} = 48$, fig. 1 shows the discrete level functions resulting from a simulation of the process. The phase difference between discrete levels (y-axis) is equal in each plot as expected for an optimum wavelength configuration. A multiplicative intensity noise of 2.5% has been applied to the cosine intensity fringes which is representative of scientific CCD cameras and is a primary source of phase noise.

The number of fringes that may be numbered to 6σ reliability for a system with λ wavelengths is given by (from equation (2))

$$\sqrt[\lambda-1]{N_{\lambda 1}} \le \frac{2\pi}{6\sqrt{2}\sigma_\phi}. \quad (6)$$

The reliability of the process only depends on the first and last wrapped phase maps with all intermediate values

for other wavelengths cancelling out (see equations 4 and 5). As the last wavelength corresponds to zero fringes, rather than performing a phase measurement here it is more accurate to set the wrapped phases for this wavelength to zero. Hence the process reliability depends only on the error in the wrapped phase map at N_{f_0}. Therefore, as the number of wavelengths used is increased the process reliability remains unchanged and the number of fringes that may be labelled increases as given by equation 6.

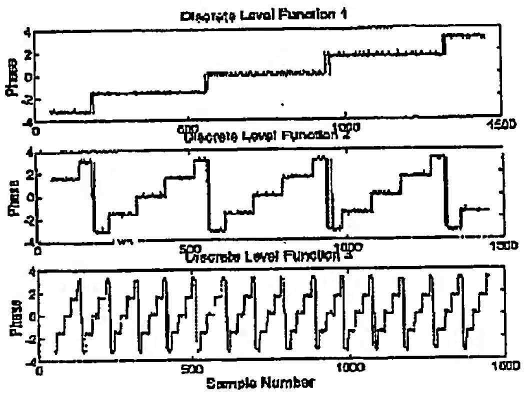

Fig. 1. Discrete level heterodyne functions for an optimum 4-λ process.

It should be noted that in the example of figure 1, the value $(N_{f_0})^{\lambda-1}$ is an integer and therefore the discrete levels are equal in phase values for each discrete level function. For any real positive number, $(N_{f_0})^{\lambda-1}$, the algorithms function correctly. For example, $N_{f_0} = 80.765$ and using 4 projected fringe wavelengths the discrete level functions are given in figure 2. The recursive unwrapping process correctly unwraps successive beat fringes to obtain the fringe order, as seen in figure 3.

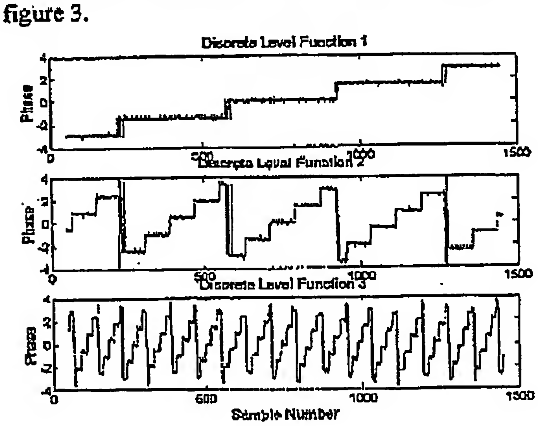

Fig. 2. Discrete level heterodyne functions for an optimum 4-λ process with a total of 80.765 fringes.

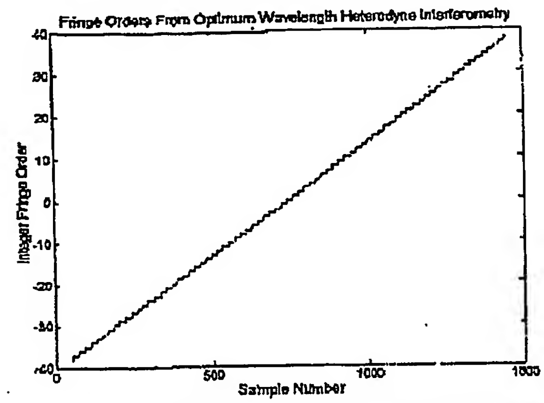

Fig. 3. Fringe Order calculated for an optimum 4-λ process with a total of 80.765 fringes.

For a typical four wavelength system $\sigma_\phi = 2\pi/85$ and the number of fringes that can be correctly identified with 6σ reliability is >1000, giving a dynamic range of >85000. The following table shows values for N_{f_0} and dynamic range for a range of λ and σ_ϕ.

Phase Noise (rms, radians)	*Optimum 3-λ Heterodyne* N_{f_0}	*Dynamic Range*	*Optimum 4-λ Heterodyne* N_{f_0}	*Dynamic Range*
$2\pi/50$	35	1,736	205	10,230
$2\pi/100$	139	13,889	1,637	163,700
$2\pi/200$	556	111,111	13,095	2,619,000
$2\pi/400$	2,222	888,889	104,707	41,902,800

Table 1: Numbers of fringes and dynamic range obtained with 99.73% reliability for optimum 3-λ and 4-λ heterodyne processing.

3.1.3 Alternative Algorithms for Generating Optimum Wavelengths

There are alternative ways to calculate the numbers of fringe used at each wavelength that result in optimum configurations in the discrete level functions. For example with 3 wavelengths, N_{f_0}, $N_{f_0} - \sqrt{N_{f_0}}$, $\sqrt{N_{f_0}} - 1$. Correspondingly modified expressions are then needed to form the heterodyne functions, equations 4 and 5 may than be applied as before. It is expected that the noise floor is worse in this case as it relies on the difference of a greater number of fringe sets.

3.1.4 Modifications to the Theoretical Description

To allow for experimental error in obtaining exactly the number of fringes required across the measurement range, the wavelengths would be selected close to their theoretical values but in such a way as to define an unambiguous measurement range slightly larger than that required. Therefore, in practical systems it would be common to use N_{f_0}, $N_{f_0}-0.7$, $N_{f_0}-\sqrt{N_{f_0}}$ for a three wavelength system.

4.0 Experimental Demonstration

A whole field, triangulation based shape measurement system is given as the exemplar for the theoretical analysis. This consists of a coherent fibre fringe projector, which produces a pattern of Young's fringes across the test object. A CCD camera is then placed at an angle to the illumination direction to view the fringes, see fig. 4. Increasing the number of projected fringes or the angular separation between the CCD and the fringe projector increases the sensitivity to the depth (z) of the test object. One of the output fibres was wrapped around a cylindrical PZT to allow the optical phase to be modulated. An existing servo control system allowed the phase of the projected fringes to be stabilised by monitoring the reflections from the distal ends of the output fibres at the 4^{th} arm of a directional coupler. The servo also enables accurate 90° phase steps to be obtained [11].

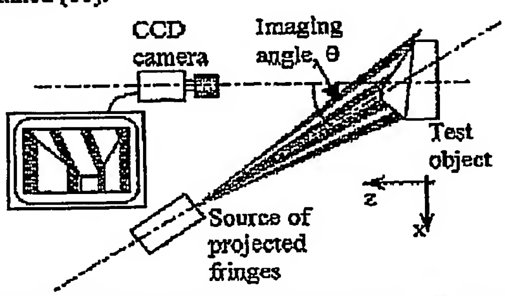

Fig.4. Experimental setup for fringe projection shape measurement

A second CCD camera was incorporated into the fringe projector to measure the fibre separation, and hence the number of projected fringes. The fringes were sampled directly onto the second optical sensor via a polarising beamsplitter. A measurement of the phase distribution across the CCD gives the fibre separation and hence the number of projected fringes [9]. We have demonstrated a resolution of <10 nm in the fibre separation measurement compared to a 50 nm requirement predicted by a simulation for 3 projected wavelengths.

To demonstrate the process, the flat side of an object was assessed initially as this gave easy verification of the fringe order calculation. Three wavelengths were used (from equation 3) with 100, 99 and 90 projected fringes.

Fig. 5 shows the result of applying equations 4 and 5 to the three wrapped phase maps obtained. The central fringe is automatically identified by the heterodyne process and is coloured black. The fringe orders are clearly identified as a repeating scheme of 6 colours either side of the central fringe.

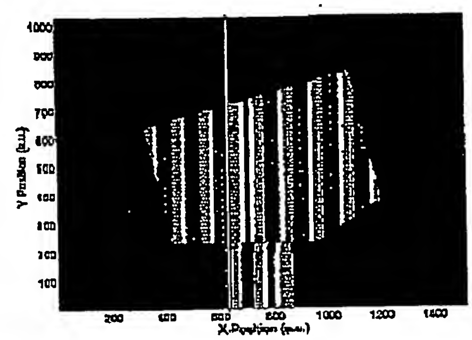

Fig. 5. Experimental fringe order map for optimum 3-λ heterodyne processing (pseudocolour representation)

The phase resolution obtained was estimated to be $1/80^{th}$ fringe principally limited by the random speckle phase which contributes to the interference phase. With $\sigma_\phi = 2\pi/80$ and $N_{f_0} = 100$ equation 2 can be manipulated to determine the fringe order numbering reliability expected from theory which evaluates to 99.2%. A local neighbourhood check applied to the central flat area of the experimental data in fig. 3 shows the number of pixels giving the correct fringe order to be 99.52%. Therefore, a validation of the process and the underlying theory has been demonstrated.

The new process is equally applicable to white light fringe projectors based on spatial light modulators or on custom gratings produced on glass substrates. Compared to the reverse exponential temporal unwrapping scheme [8], to measure over ~100 fringes requires 8 wrapped phase maps to be obtained. Therefore, the use of the new algorithm enables a reduction in data acquisition time and data space of >60%. The dynamic range obtained in this measurement was 1:8000. Furthermore, the process is applicable to any form of interferometric sensor where phase measurements are available at defined sensitivities (wavelengths).

5.0 Claims

The following claims are made.

1. A method for absolute fringe order calculation in multi-wavelength interferometry.
2. The wavelengths are selected in an optimum manner such that discrete level heterodyne functions contain equal numbers of levels in the interval $-\pi$ to $+\pi$.

3. A recursive unwrapping algorithm has been formulated to determine the absolute fringe order from the discrete level functions.
4. The use of a phase noise measure (the standard deviation phase noise) provides a means to quantify the reliability of the fringe order calculation.
5. A set of mathematical relationships embodying claims 1, 2 and 3 defining: the wavelengths to be used, a scheme to form the discrete level functions, and a procedure to unwrap these functions at each pixel independently.

$$N_{f_i} = N_{f_0} - \left(N_{f_0}\right)^{\frac{i-1}{\lambda-1}}, \quad \text{for } i = 1,2,\ldots,\lambda \qquad \text{(a)}$$

$$DL_i = H_{0,i} - \frac{N_{f_0} - N_{f_i}}{N_{f_0} - N_{f_{i+1}}} \times H_{0,i+1}$$

$$IDL_{i+1} = NINT\left[\left(DL_i + 2\pi \times IDL_i\right) \times \left(\frac{N_{f_0} - N_{f_{i+1}}}{N_{f_0} - N_{f_i}}\right) \times 2\pi\right]$$

The number of fringes heterodyned to 6σ reliability is given by:

$$\sqrt[\lambda-1]{N_{\lambda 1}} \leq \frac{2\pi}{6\sqrt{2}\sigma_\phi} \qquad \text{(b)}$$

6. A modification of claim 5 where the second wavelength ($i = 2$, equation (a)) is modified by up to 30% in order to guarantee forming less than 1 beat fringe across the desired measurement range.
7. An alternative scheme for generating the optimum wavelengths and discrete level functions, which for a 3 wavelength system are defined by N_{f_0}, $N_{f_0} - \sqrt{N_{f_0}}$, $\sqrt{N_{f_0}} - 1$.
8. The process reliability may be defined to other values. For example, to obtain 8σ reliability, equation (b) above becomes:

$$\sqrt[\lambda-1]{N_{\lambda 1}} \leq \frac{2\pi}{8\sqrt{2}\sigma_\phi}$$

9. The process is applicable to any form of interferometer, not just to fringe projection as exemplified herein.

6.0 Essential Features of the Invention

1. A mechanism to produce a phase measurement at a number of discrete wavelengths.
2. The wavelength range required is dictated by equations (a) claim 5 or the equations in claim 7.
3. A means by which the wavelengths (or the number of fringes across the measurement range) can be measured.
4. A computer system to implement the data processing scheme and control of the data acquisition process.

7.0 Non-Confidential Description of the Invention

This invention concerns the development of a robust measurement process based on multiple wavelengths, phase measurement and heterodyne processing. It is shown that given a certain phase measurement noise it is possible to maximise the number of fringe orders unambiguously identifiable and therefore the measurement dynamic range. Each fringe order can be identified as an absolute number. A robustness measure based on Gaussian statistics is also derived for the process.

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